

ARMY RESEARCH LABORATORY



XM194 Gun Mount Shield: Processing in a Female Tool Utilizing Embedded Sensors for Process Control

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Abstract

This report addresses the use of U.S. Army Research Laboratory (ARL) and industry technologies to prototype the XM194 gun mount shield. The prototyping was done with novel ideas and techniques in mind. It was used as an advanced technology demonstrator for sensor-based process control. First, a brief description of the XM194 gun mount shield is given. Second, Seemann's Composite Resin Infusion Molding Process (SCRIMP) was used as a fabrication process, which is possible through the establishment of a Cooperative Research and Development Agreement (CRADA) with SCRIMP Systems, Inc. Third, the state-of-the-art Sensors Mounted as Roving Threads (SMARTweave) system is detailed, along with the sensor-based control methodology utilized in the process. Fourth, the successful processing of the XM194 gun mount shield is illustrated. Finally, several possibilities for future sensor process and process control work are discussed.

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1. Introduction

The prototyping of the XM194 gun mount shield was done with novel ideas and techniques in mind. It was used as an advanced technology demonstrator for sensor-based process control. Seemann's Composite Resin Infusion Molding Process (SCRIMP) was used as a fabrication process. This report addresses the following points. First, a brief description of the XM194 gun mount shield is given. Second, SCRIMP, which is possible through the establishment of a Cooperative Research and Development Agreement (CRDA) with SCRIMP Systems, Inc., is described. Third, the state-of-the-art Sensors Mounted as Roving Threads (SMARTweave) system is detailed. Fourth, the actual processing of the ballistic shield is illustrated. Finally, several possibilities for future work are discussed.

2. XM194 Gun Mount Shield

The XM194 gun mount shield, as shown as part of the 155-mm, advanced, solid propellant, armament system in Figure 1, is composed of an S2-Glass composite armor. This component was designed as composite material and has some structural requirements, but its primary purpose is ballistic. The shield protects the cooling and recoil mechanisms. The intentions of this project were to prototype the "ballistic shield."

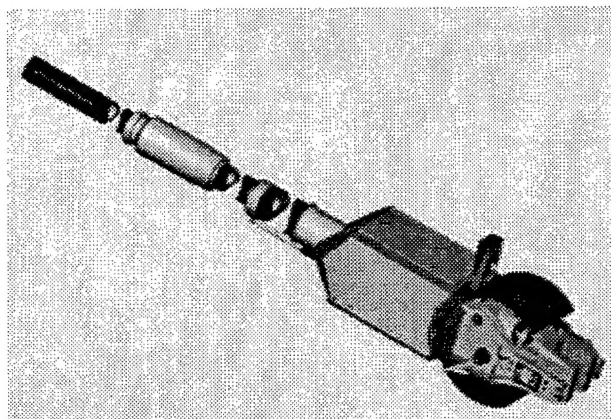


Figure 1. The 155-mm, Advanced, Solid Propellant, Armament System, Including XM297E1 Cannon Assembly, Laser Ignition System, and XM194 Gun Mount.

SCRIMP is a process that is currently manual in nature. The preform manufacturing and the resin mixing are done by hand. The process is controlled by an experienced engineer. Currently, SCRIMP is an "art" not a science. However, new research on SCRIMP is geared toward automating or computer-controlling several steps of the process. The closest component to computer control is the resin mixing. In fact, a machine is being manufactured by Accudyne, for Hard Core DuPont, that will mix all the resin components in line to exact quantities. This advancement will allow for variable resin contents throughout the component in an effort to minimize exothermic reactions. Another advancement could be preform manufacturing. Mass production of preforms is possible; however, it has not been emphasized because SCRIMP is currently used in low-volume manufacturing. This could be done if higher production rates are required.

The most difficult process automation to address is the infusion process itself. Simple infusion schedules can be automated but are often not optimal. The difficulty arises when the infusion is to be optimized. Optimization can be done by the process designer using Darcy's law for flow approximation in a finite element environment. These models and their validation are being researched in the academic world. True optimal processing could be accomplished by monitoring the flow-front progression and comparing it to an optimized-flow model, then basing control decisions to force the flow front to follow the optimal path. Based on the flow-front state, control algorithms exist to control many things, like flow rate, temperature, and pressure. The ability to control the process still hinges on the knowledge of where the flow front is. That is where SMARTweave comes into play.

4. SMARTweave

SMARTweave has undergone a series of innovations since it was first patented [2]. The SMARTweave system consists of two planes of conductive threads in an orthogonal, noncontacting grid. The two layers are separated by plies of insulative preform. A 12-V, direct-current (DC) signal is sent through one of the planes of sensors, which are called the excitation lines. The second plane

of sensors, called the sense lines, measure the current that passes through the junction. Figure 3 depicts the general circuit schematic for the SMARTweave system.

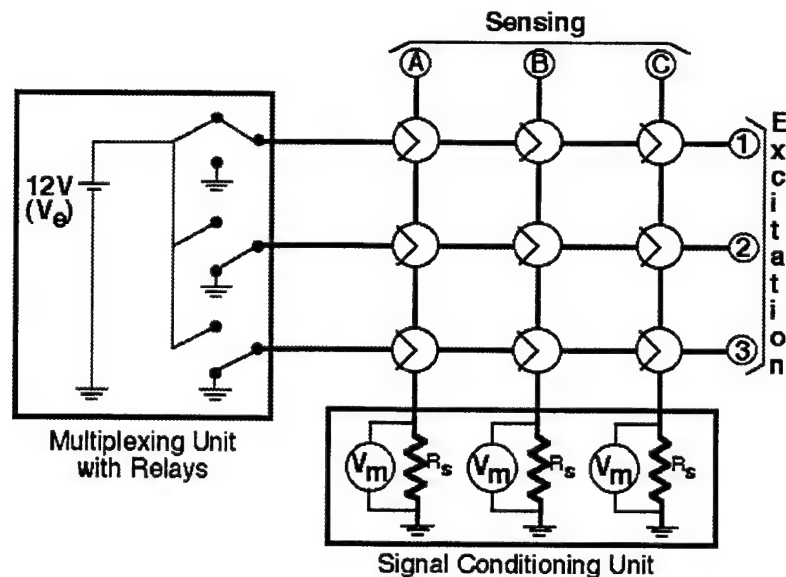


Figure 3. SMARTweave Circuit Schematic Depicting a 3-Excitation \times 3-Sense Line Grid.

The polymeric resin material, which serves as the matrix for the composite, contains ions that are free to move within the fluid. SMARTweave utilizes this fact, and, as the resin fills the preform, the two planes of sensors form a series of connected circuits. The sense lines measure the voltage that can cross the gap between the two planes. Since a DC current is utilized, only the ionic mobility of the resin is being measured. Therefore, the resin acts as a variable resistor, and, the lower the resin resistance, the higher the overall SMARTweave signal.

The SMARTweave system consists not only of the electrical sensing grids but also of a series of hardware and software components. First, a signal-conditioning unit, which was custom made for the U.S. Army Research Laboratory (ARL) by Waibel Technical Computing (WTC), contains the 12-V, DC power supply, as well as the mechanical relays used to switch from one excitation line to another. A National Instruments SCXI-1000 Chassis with a 1300 module controls the sense lines. A Dolch L-PAC 586 portable computer is used to collect and analyze the data. The software that acquires the data runs on National Instruments LabVIEW Version 3.0.

The user is faced with five main options upon entering the SMARTweave software package, as depicted in Figure 4. The sampling rate may be defined in the grid. At this point, the system has a maximum capacity of a 16-excitation \times 16-sense lines, for a total of 256 nodal locations. However, not all sensors must be utilized at once. In the faces option, the user may define not only the number of sensors to collect data but also the geometry of the grid orientation and nonexcited nodes. Figure 5 illustrates the typical flow screen seen by the operator. In this case a 6-excitation \times 6-sense grid has been chosen, where each block corresponds to a specific voltage at the respective node. The flow front of the resin may be depicted on this flow graph. Not only can one view the overall picture of the resin infusion, but one may also focus upon the voltage value at individual nodes using the grid probe. The cure graph displays real-time voltage vs. time data for any series of user-defined node combinations. The logging period, file name, and elapsed time are displayed on the FLOW screen. The elapsed time may be defined to correlate with any zero time, such as initial point of infusion or addition of the catalyst in order to judge time until gelation. The SMARTweave FLOW screen also allows the user to transfer real-time-voltage data across the internet. This allows for advanced numerical analysis, using a Silicon Graphics (SGI) Workstation in real time.

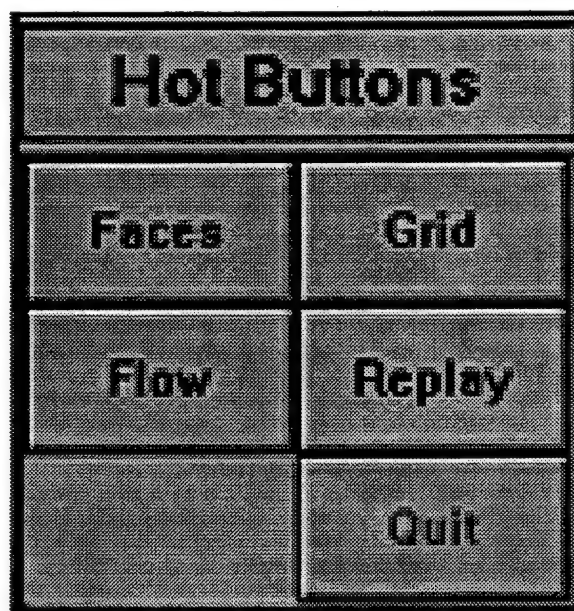


Figure 4. Five Main Options Upon Entering the SMARTweave Software Written on LabVIEW 3.0.

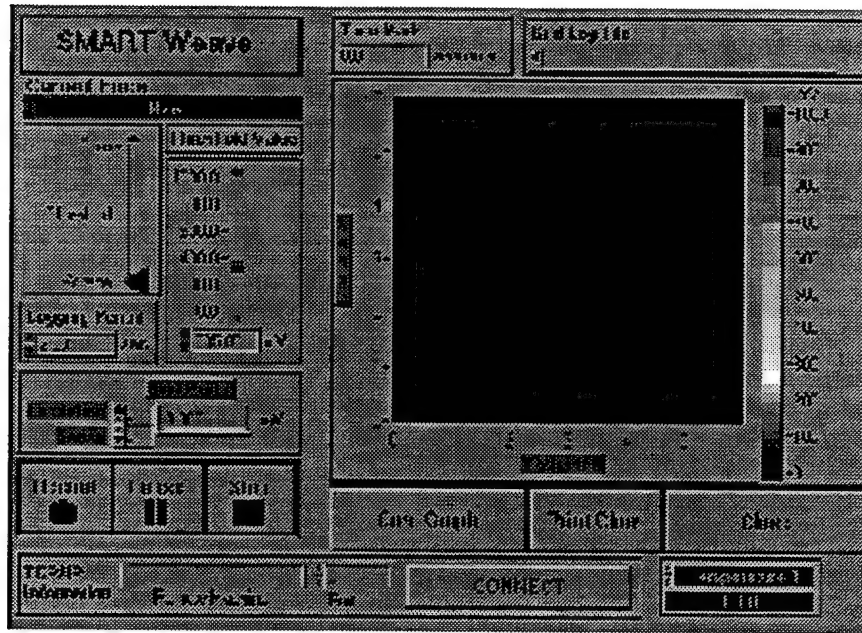


Figure 5. The Real-Time Voltage Data May Be Viewed, Recorded, and Transferred Over the Internet in the FLOW Option.

Once the data have been recorded, the portable system has the option of replaying the data at any time. As Figure 6 shows, the replay screen has many of the same features as the FLOW screen, including overall flow grid, grid probe, and cure graph. In this example, a point infusion and line vacuum source along the last excitation line were tested. SMARTweave monitored the semicircular flow pattern induced by the experimental setup using glass preform and an epoxy resin. The data may also be exported in any format with a defined amount of data points. Another feature of the replay screen is the ability to view thermal profiles recorded using a series of thermocouples, which are independent of the SMARTweave grid.

There are numerous applications of the SMARTweave system in the area of process control of composite materials manufacturing and damage detection. It is particularly beneficial to have the ability to visualize the resin flow front in RTM and other two-sided tooling processes. Often, complex geometric shapes provide a greater risk of forming dry spots or areas that are not fully wetted by the resin. With the use of SMARTweave, the flow front may be visualized during the infusion process. With such on-line techniques, many changes could be made during the infusion

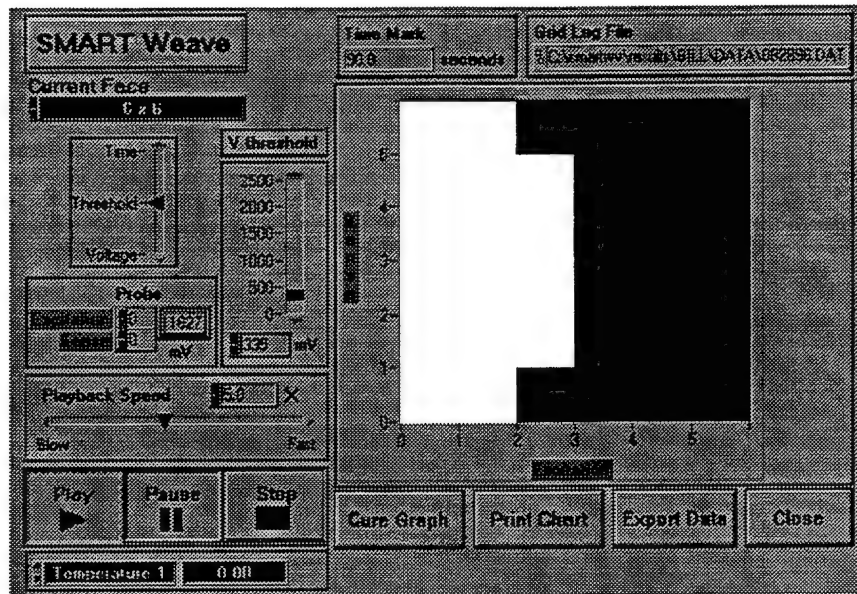


Figure 6. The REPLAY Option Allows One to View, Print, or Export Previously Recorded Data.

to ensure full wetting of the part, such as altering inefficient vacuum ports, increasing incoming fluid flow, and adjusting pressure. By knowing the geometry of the sense lines, the resin position may be correlated with time. Such information allows the user to estimate the overall filling time by calculating the incoming resin velocity. Flow simulations may also be verified with the correlated time vs. position of resin data that the system records. The capability to visualize the flow of resin throughout the thickness of the part provides numerous applications in the area of process control.

Research is ongoing at the University of Delaware's Center for Composite Materials to relate the voltage signal to the cure of the polymer. Since a DC voltage is used to measure the ionic mobility of the fluid, the extent of cure can be monitored by comparing relative voltages. During the cure of thermoset resins, crosslinking of the polymer chains occurs. The increase in crosslinking density results in diffusion limitations of the ions. As the ionic mobility becomes restricted, the corresponding voltage signal is reduced. The change in voltage signal output may be used to relate the change in viscosity of the resin, assuming a constant temperature. Such significant information is crucial for SCRIMP, since the time of infusion is limited by the resin viscosity. The extent of cure of the system may be monitored using similar techniques. Predicting the extent of cure of the part

in-process allows an accurate determination of demold time. In doing so, a higher production may be achieved and therefore result in a more economical use of the tooling.

The embedded sensors may also be utilized after the infusion process is complete. ARL is investigating the possibility of SMARTweave as a damage-detection mechanism. A conductivity test may be conducted along the sensors both before and after the part is ballistically impacted. As the part is damaged, delaminations are created throughout the part causing the sensor/matrix interface to separate. A comparison of the resistances along the sensors allows one to correlate the extent of impact. This ability would be best served with a sensor material whose resistance is sensitive to strain.

SMARTweave may be used over a range of fluid resistances. As one might expect, the lower the resin's impedance, the higher the initial voltage. Applied Polyamic's SPH4, a low-impedance phenolic resin has been tested in the crew capsule of the composite armored vehicle (CAV). Applied Polyamic's SC4 moderate-impedance Epoxy system was applied in the lower hull of CAV. Most of SMARTweave's experimentation has been performed using vinyl ester, or high-impedance resins. Specifically, over 50 flat plates have been produced, which incorporated both mechanical and chemical characterization for SMARTweave. Dow's Derakane 510a-350, 2.0 weight-percent, Akzo's Trigonox 239A, and 0.2 weight-percent Mahogany's CoNAP were in the fabrication of the ballistic shield.

Figure 7 depicts an example of the previously discussed cure graph for the SC4 epoxy system. Additional thermal energy was required to fully cure this epoxy system. Therefore, SMARTweave's data were used to monitor not only cure changes but also temperature fluctuations. Initially, the resin was infused into the part at room temperature, as shown by the sudden increase in voltage at time zero. The sudden decrease in slope was caused by parallel circuit creation as the part filled. The voltage stabilized as a steady state was reached, indicating the part had been fully wetted out. At this point, the tool's temperature was increased to 60° C. The SMARTweave signal followed this change, since viscosity of the resin decreased with increasing temperature, as indicated by the first increase in slope. The second steeper rise in the voltage signal was caused by the autocatalytic

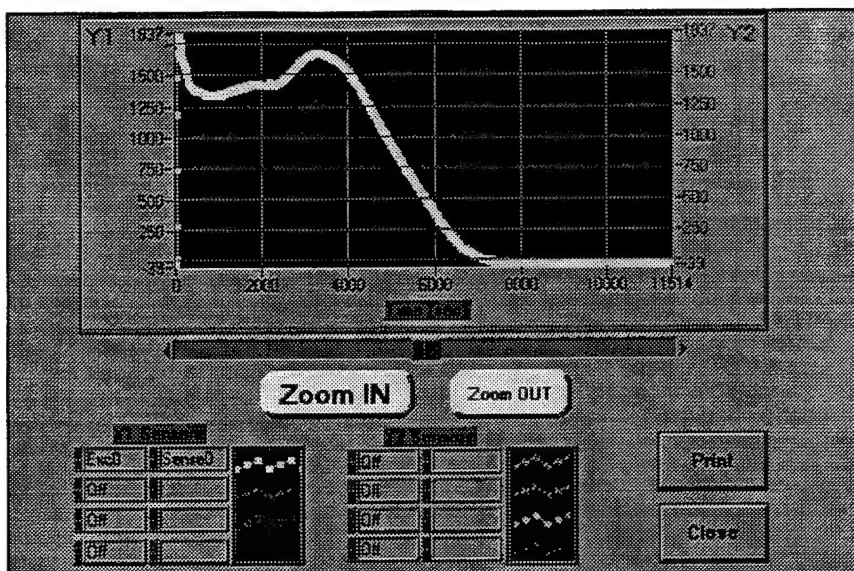


Figure 7. Cure Graph Represented as Voltage vs. Time for SC4 Epoxy System. The Part Was Infused at Room Temperature and Then Ramped to 60° C at 1,200 s. SMARTweave Monitored the Change in Temperature as Indicated by the Varying Voltage Signal.

(exothermic) reaction of the resin. The top of the peak indicates where diffusion limitations began to take over. At this point, the ionic mobility was limited due to extensive crosslinking, and the sensed voltage began decreasing at a constant rate.

5. Processing of the Ballistic Shield

The most recent application of the SMARTweave system was in the production of prototype XM194 Ballistic Shields, as shown in Figure 8. The ballistic shield protects the recoil and cooling mechanisms of the 155-mm cannon. The female tool, as illustrated in Figure 9, was used in conjunction with SCRIMP to manufacture the shield. Since the part is considered a thick-section composite, the resin-flow front needed to be monitored at the surface of the tooling. Therefore, 16-sense lines were placed three layers above the mold surface. Next, two layers of the glass fabric were laid down to separate the sensor planes. Then 16 excitation lines were placed orthogonal to

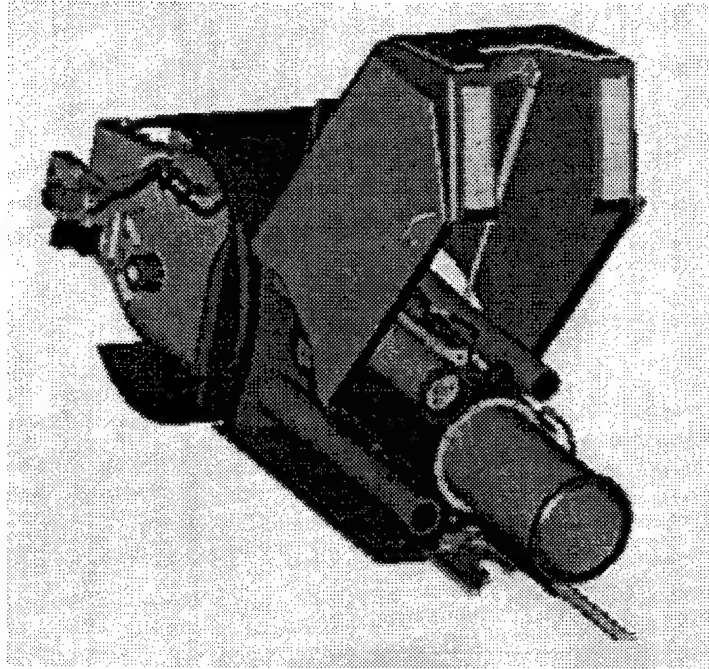


Figure 8. SMARTweave Was Implemented in the Production of the XM194 Ballistic Shield, Which Protects the Recoil and Cooling Mechanisms of the 155-mm Cannon.

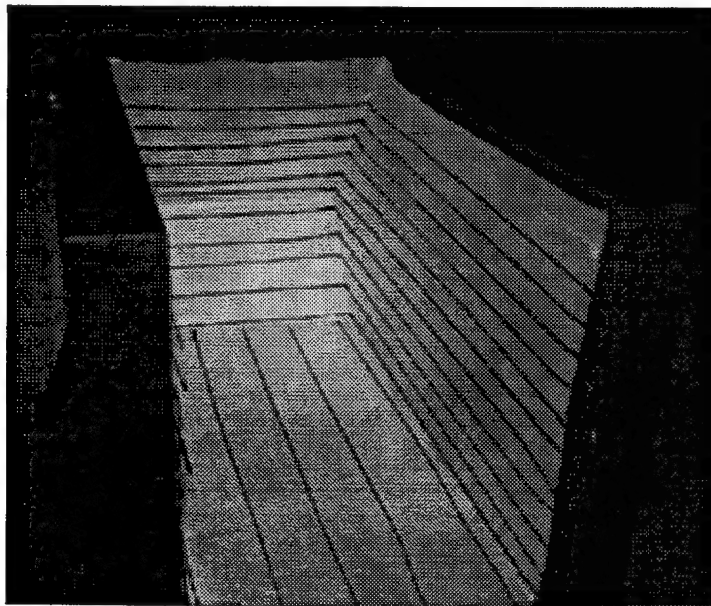


Figure 9. Female Tooling Used to Manufacture the Ballistic Shield With the First Several Layers of Glass Preform and the First Plane of Embedded SMARTweave Sensors Made of 12k Carbon Tows.

the sense lines. In this case, 12k carbon tows were used as sensors. Seven spiral tubes were placed along the length of the shield on the top layer, and the preform was bagged, as depicted in Figure 10. By placing the sensors near the tooling surface, the resin flow front at the tool may be monitored. The flow visualization was used in this case to control the inlet and vacuum ports. Initially, only the center of the seven tubes served as an inlet port and the remaining six drew a vacuum. As the resin reached the adjacent line, it was to be switched from a vacuum line to another injection source. One cannot rely on visual techniques to make this conversion. It has been shown at ARL that a dry line would result along the bottom of the part just before the injection source if the injection is begun too soon, since the top layer of resin did not correlate to the flow front at the tooling surface. Using SMARTweave to monitor the flow front, a through-thickness analysis could be achieved. With knowledge of the relative distances between the nodes, the software's flow diagram indicated when the resin had reached the next tube. At this point, the switch from vacuum port to resin injection was made.

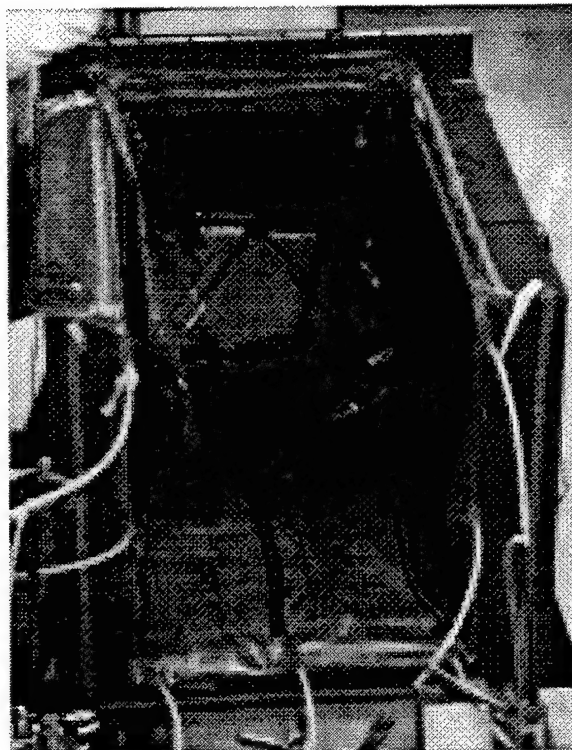


Figure 10. SMARTweave Was Used in the SCRIMP Process to Control the Infusion Ports and Vacuum Vents in the Manufacturing of the Ballistic Shield.

A sample voltage vs. time cure graph for the vinyl ester resin system used for the Ballistic Shield is found in Figure 11. In this case, unlike the epoxy, no external heat was added during the curing process. Therefore, the highest voltage signal correlated to the initial point of infusion, which had the least amount of crosslinking of the thermoset resin. The signal continued to decrease uniformly with time as the ions became more restricted in their movement. Figure 12 depicts the final ballistic shield, with the remaining embedded SMARTweave sensors.

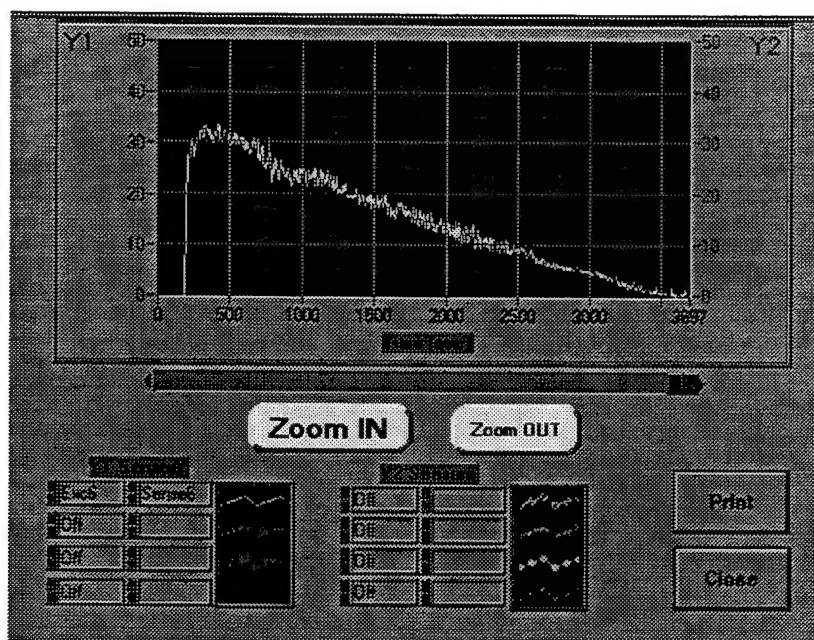


Figure 11. The Cure Graph Voltage vs. Time for a Single Node for the Vinyl Ester System That Was Used as a Matrix Material in the Ballistic Shield. The Part That Was Cured at Room Temperature Depicts a Steady Decrease in Voltage Signal as the Resin's Ionic Mobility Was Reduced.

6. Future Work

This work has shown two different advancements that will be investigated. The potential for SMARTweave to serve as a damage detection device has been shown first. As shown in Figure 13, the sensors, when broken, will register a change in resistance. Upon material advancements in sensor type, this application could be optimized to yield a thorough, health-monitoring system.

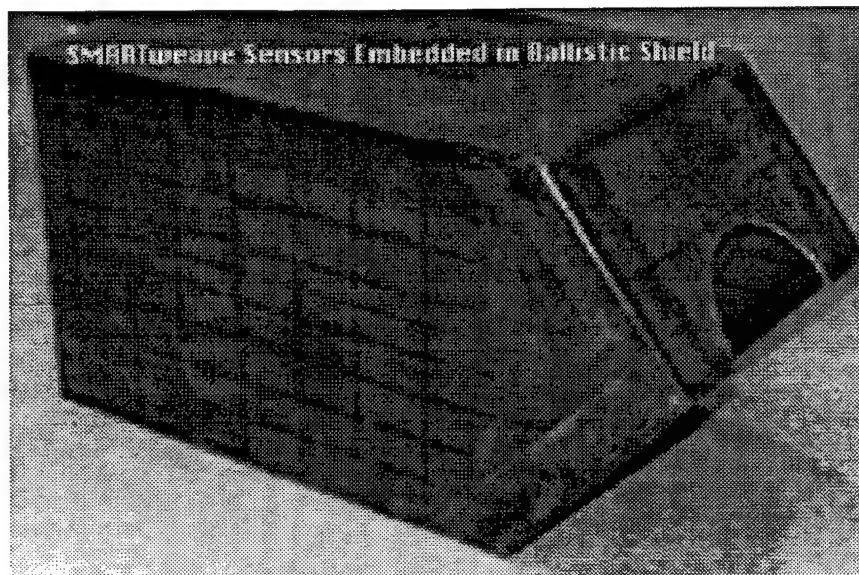


Figure 12. The Completed Quarter-Scale Thickness Prototype With 32 Embedded SMARTweave Sensors.

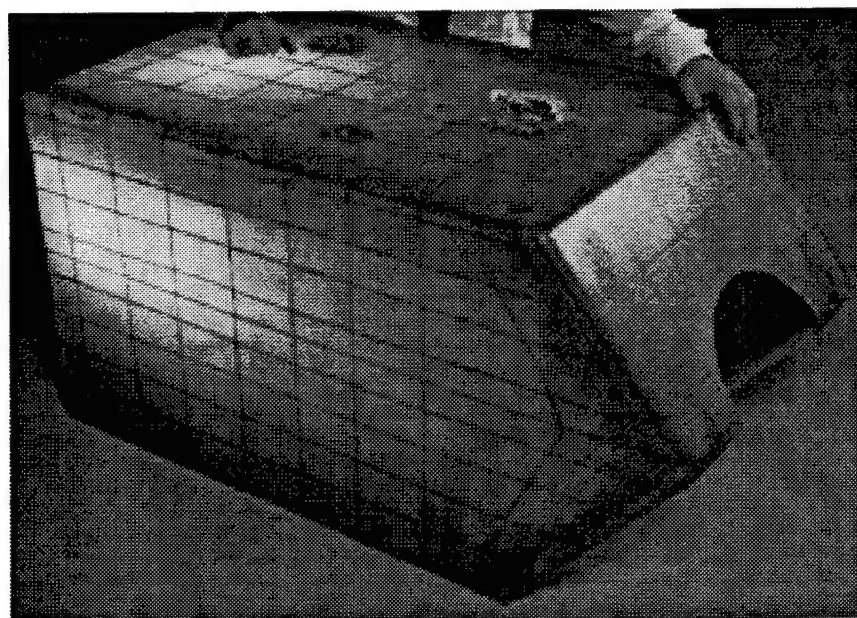


Figure 13. SMARTweave's Damage-Detection Capability, as Demonstrated by Ballistic Impacts on the XM194 Gun Mount Shield.

Second, similar processing on a male tool would have certain advantages to processing in a female tool, such as ease of lay-up. Based on that understanding, a male tool has been designed and attempts will be made to fabricate a Ballistic Shield.

7. Conclusions

In summary, SCRIMP is an excellent fabrication method for large-scale, thick-section composite materials, such as the XM194 gun mount shield. It has been shown that SMARTweave has numerous applications specifically related to composite process control. It may be used as a mechanism for both flow monitoring and control of the inlet and vacuum ports in a SCRIMP environment. Finally, several new areas of research have been founded, including damage detection and SCRIMP on a male tool. Overall, the prototyping of the XM194 gun mount shield has been a tremendous success.

8. Reference

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2. Walsh, S. W. "In-Situ Sensor Method and Device." U.S. Patent No. 5, 210, 499, 11 May 1993.

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